Case Studies in Thermal Engineering 2 (2014) 62–66

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

A case study on compatibility of automotive exhaust thermoelectric generation system, catalytic converter and muffler

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ARTICLE INFO

Article history:
Received 5 December 2013
Received in revised form
2 January 2014
Accepted 2 January 2014
Available online 23 January 2014

Keywords:
Automotive exhaust heat
Back pressure
Heat exchanger
Catalytic converter
Bench test

ABSTRACT

The power generation of an exhaust TEG (thermoelectric generator) depends on heat energy and thermoelectric conversion efficiency. However, there are compatibility problems among TEG, CC (catalytic converter) and muf (muffler). The present work tried to vary the installation position of TEG and propose three different cases. Case 1: TEG is located at the end of the exhaust system; case 2: TEG is located between CC and muf; case 3: TEG is located upstream of CC and muf. Simulation and experiment were developed to compare thermal uniformity and pressure drop characteristics over the three operating cases. From the simulation and experiment, heat exchanger in case 2 obtained more uniform flow distribution, higher surface temperature and lower back pressure than in other cases. At the same time, the CC and muf could keep normal working in case 2, providing a theoretical and experimental basis for the exhaust gas waste heat recovery system.

1. Introduction

In recent years, because of the forecast limitations in oil supply and increasingly stringent vehicle exhaust gas emission regulations such as Euro 6, new energy technologies are being developed to improve fuel efficiency and reduce emission; examples include hybrid vehicles as well as those powered by fuel cells and hydrogen [1]. For gasoline engine, about 40% of the primary gasoline energy is discharged as waste heat in exhaust gas [2]. Historically, several types of heat exchangers and different heat transfer enhancement measures such as ribbing, grooving and protrusions have been investigated since the first automobile thermoelectric generator (TEG) was built in 1963 [3]. Chung et al. investigated a thermoelectric energy generation system which used a thermoelectric module (TEM) generator. The main feature of their study was the use of high temperatures (up to 200 °C) to ensure TEG reliability, especially for diesel engines, whose exhaust gases are at temperatures from 200 °C to 300 °C at the outlet of the catalyst filter [4]. Thacher et al. employed a rectangular, 1018 carbon steel compact heat exchanger with offset strip fins for a 5.3 L V8 gasoline engine [5]. With the same requirements for exhaust heat exchanger in vehicle waste heat recovery by a Rankine cycle, a shell and tube counter flow heat exchanger was used with exhaust gases in tubes and working fluids in shell [6].

However, there are compatibility problems among TEG, CC (catalytic converter) and muf (muffler). Both TEG and CC need heat to keep normal working in the vehicle exhaust system. The pressure drop directly affects the back pressure of the

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http://dx.doi.org/10.1016/j.csite.2014.01.002

engine exhaust gas, and then the intake and exhaust system of the engine is also affected, which may reduce the engine power. The interaction between them when they are both installed in the automobile exhaust system would cause improper working [7]. The present work tried to vary the installation position of TEG and propose three different cases. Case 1: TEG is located at the end of the exhaust system; case 2: TEG is located between catalytic converter (CC) and muffler (muf); case 3: TEG is located upstream of catalytic converter (CC) and muffler (muf).

A test bench was developed to compare thermal uniformity and pressure drop characteristics over the three operating cases, which provided a theoretical and experimental basis for the exhaust gas waste heat recovery system.

2. Modeling

Fig. 1 presents a plate-shaped heat exchanger of the TEG: diameters of the intake manifold and the exhaust manifold of the heat exchanger are both 36 mm. There are two small fins set at the entrance for diverting the flow, so that the high-temperature exhaust gas is diffused in the entire lateral area rather than concentrating in the central region; many small fins are disorderly set in the internal structure for disturbing the flow, so that the exhaust gas can be fully in contact with the metal walls of the heat exchanger and stays longer in the cavity of the heat exchanger, which can increase the heat that airflow transfers to the fins. Thereby the energy of the high-temperature exhaust gas can be absorbed effectively.

The catalytic converter, whose depth is 200 mm and thickness is 5 mm, is a cylindrical shell with a 50 mm radius. The muffler, whose depth is 150 mm and thickness is 5 mm, is an elliptic cylindrical shell with a 43 mm and 70 mm radius.

3. Simulation

3.1. Boundary

A 2.0-L naturally aspirated engine was used as a study object. Its performance data are listed in Table 1. According to the relevant parameters, the engine exhaust velocity reaches 20 m/s when the engine rotation speed is 2800 r/min and the gas inlet temperature is about 350 °C, which is measured by a thermocouple. So the gas inlet temperature is set to 350 °C and the inlet flow velocity can be set to 20 m/s. The exit faces the atmosphere, so the pressure at the exit is approximately standard atmosphere pressure, and the back pressure at the exit can be set to 0. Additionally, the coefficient of convective heat transfer between the outer surface of the exchanger and the air is set to 20 W/m^2 K. The coefficient of the convective heat transfer among the outer surface of the CC, the muf and air is set to 15.2 W/m^2 K.

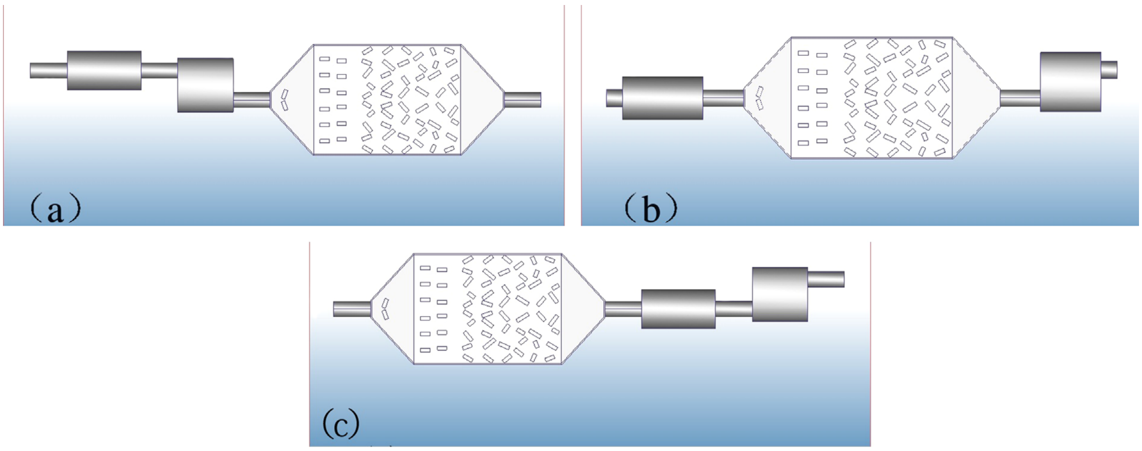

Fig. 1. Structures of three cases: (a) case 1, (b) case 2, and (c) case 3.

Table 1
The engine performance parameters.

Parameter	Value	Parameter	Value
Cylinder number	4	Governed power (kW)	108
Valves per cylinder	4	Governed speed (rpm)	6000
Displacement	1997 ml	Peak torque/speed	200 N m/4000 rpm
Bore/stroke (mm)	85/88 mm	Power of pump	0.18 kW
Firing order	1-3-4-2	Cooling mode	Water cooling
Radiator size	$547 \times 415 \times 50$ mm^3	Number of fan shift	1

3.2. Thermal analysis

The temperature distribution of the exhaust exchanger was crucial for the TEG in three aspects: firstly, it determined the available thermoelectric material by maximum continuous operating temperature; secondly, it seriously affected the energy conversion efficiency of heat to electricity; thirdly, it dominated the uniformity of thermal stress in device level and module level. A nonuniform thermal stress made the contact between TE module and heat exchanger rough, or even worse resulted in permanent damages to TEG modules [8].

The simulation results are shown in Fig. 2(a)–(c). It was general for each case: the overall temperature appeared to be of cascade distribution, the transverse temperature distribution was uniform, and the longitudinal temperature gradually reduced. The heat of the high-temperature exhaust gas was insufficient to maintain a high-temperature state in the second half of the heat exchanger after the gas was in full contact with the covers and the fins.

In case 1, TEG was placed at the end of exhausted system, so the interface temperature of heat exchanger was just 210 °C on average. The highest temperature was 240 °C at the inlet and the minimum temperature was proximately 170 °C at the outlet. Considering that low-temperature thermoelectric modules (appropriate temperature 250 – 350 °C) are used in the TEG, the temperature of heat exchanger cannot meet the module's demand.

In case 2, TEG was located between catalytic converter (CC) and muffler (muf); the averaged surface temperature of exhaust heat exchangers was 270 °C. The interface temperature of the exchanger was uniform, which met the requirement of the thermoelectric exhaust system.

In case 3, TEG was located upstream of catalytic converter (CC) and muffler (muf); the interface temperature of heat exchanger was 280 °C on average, which was beneficial for arrangement of the thermoelectric modules. However, the highest temperature of CC was 230 °C, while the lowest was 160 °C; the average temperature of CC was just 190 °C, which could not reach the ignition temperature (250 °C) of harmful exhaust gas; CC was working under an abnormal condition.

3.3. Back pressure of an exhaust gas system

The hot exhaust flowed into the exhaust gas system and transferred heat, which was bound to pressure drop for fluid. From the perspective of an automobile engine, this pressure drop was equivalent to a rise in the ambient pressure and naturally a drop in output power. In some cases, for the maximum power output, the pressure drop may be so high that the engine would stop working. It was necessary to test and evaluate pressure drop level of different cases under wide range of operating conditions.

Corresponding to the different revolving methods of the engine in the three cases, there were 9 operating conditions for the exhaust gas system. It was general for each case: the more the revolving speeds, the larger the pressure drop. As shown

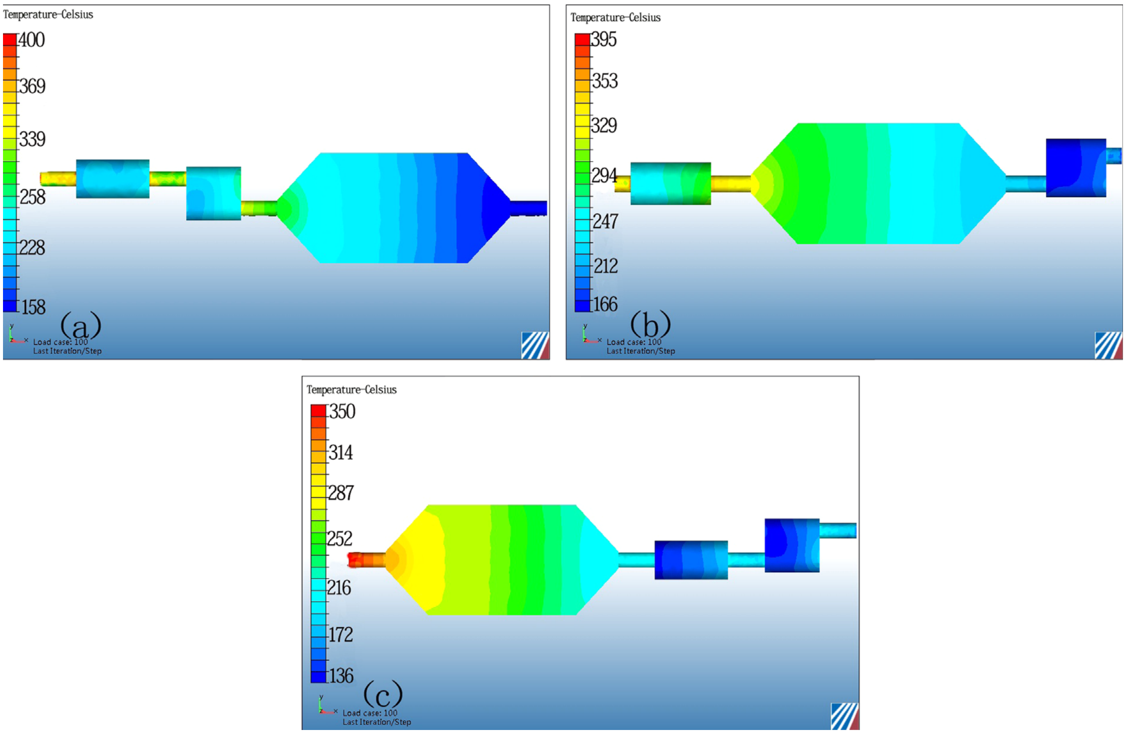

Fig. 2. Results from simulation under three cases: (a) case 1, (b) case 2, and (c) case 3.

in Fig. 3, when the engine rotation speed was 3000 r/min, the heat exchanger in case 3 was 695 Pa in pressure drop and that in case 2 was 127 Pa in pressure drop. In case 3, the high pressure drop directly affected the back pressure of the engine exhaust gas, and then the intake and exhaust system of the engine was also affected, which may have reduced the engine power. In case 2, the pressure drop of CC, muf and heat exchanger was relatively low, which met the requirement of the exhaust gas system.

4. Experimental results and discussion

The experimental system was composed of the 2.0-L naturally aspirated engine, a dynamometer (maximum power input 160 kW, maximum speed 6000 rpm). In the bench test, the experiment conditions such as room temperature, wind speed,

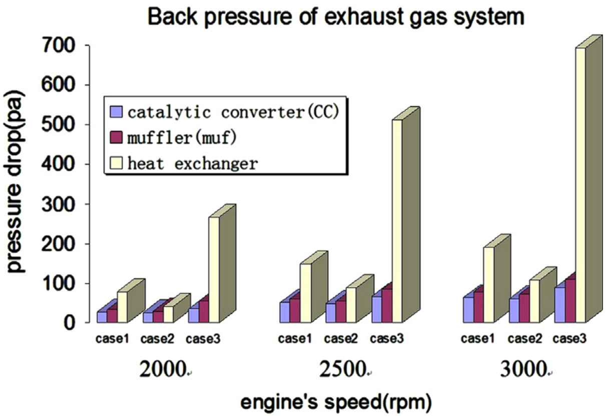

Fig. 3. Back pressure of the exhaust gas system.

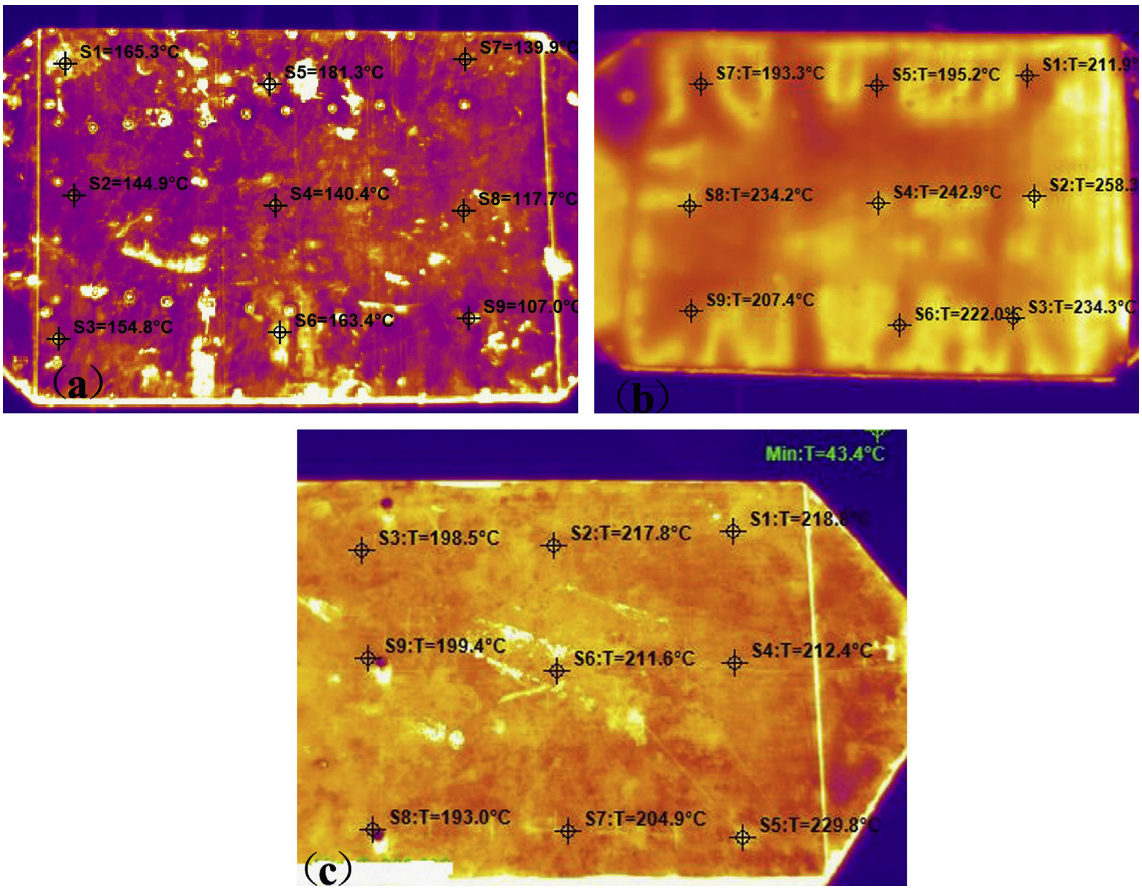

Fig. 4. Infrared thermal images of the heat exchanger under three cases: (a) case 1, (b) case 2, and (c) case 3.

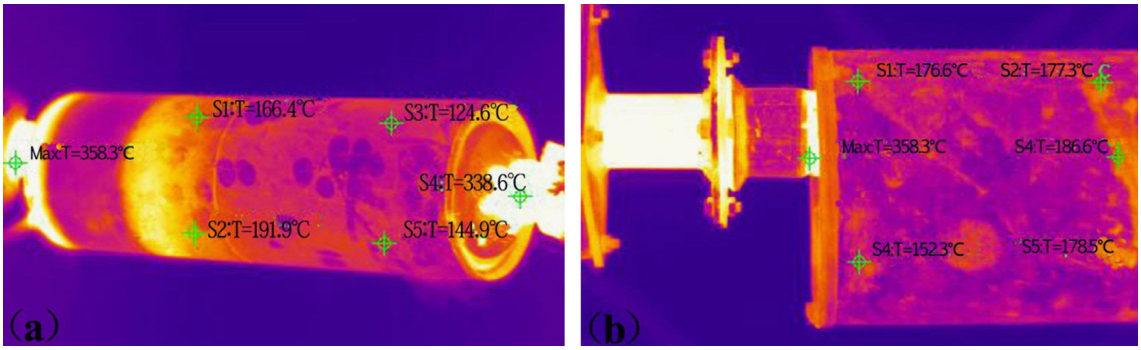

Fig. 5. Infrared thermal images under case 2: (a) CC and (b) muf.

etc. remained unchanged and the engine's revolving speed was maintained at around 2800 rpm. Several transducers were used such as pressure sensor, K-type thermocouples and infrared camera to record the temperature distribution of the exhaust heat exchanger.

Pictures of the surface temperature distribution on the heat exchangers with three cases were taken using the thermal imaging system, and compared in Fig.4(a)–(c). In terms of the surface temperature and uniformity of the whole temperature distribution, it is obvious that the experimental results for three cases are in accordance with the simulation results. Besides, the heat exchanger in case 1 has a lower average temperature and maximum temperature. The heat exchangers in cases 2 and 3 have relatively higher temperatures; they are well distributed, but CC works under an abnormal condition in case 3. Overall, case 2 tends to be adopted in the following research.

Pictures of the surface temperature distribution on the CC and muf in case 2 were taken using the thermal imaging system. The experimental results are shown in Fig. 5(a) and (b); the averaged surface temperature of CC was just 180 °C, the highest temperature appeared in the inlet and the temperature around the inlet was generally about 340 °C. At the same time, the averaged surface temperature of muf was just 170 °C, the highest temperature also appeared in the inlet and the temperature around the inlet was generally about 290 °C. There was some metal rust on the surfaces of CC and muf, causing the surface temperature low and nonuniform. From these experimental results, it is clear that the CC and muf in case 2 keep normal working.

5. Conclusion

A research was carried out to test three cases about the installation position of the thermoelectric generator. In case 2, the heat exchanger obtained a relatively high surface temperature and an ideal temperature uniformity to improve the efficiency of the TEG. The pressure drop of CC, muf and heat exchanger was relatively low, which met the requirement of the exhaust gas system. At the same time, the CC and muf in case 2 can keep normal working. So case 2 is the best.

In future study, the method of simulation modeling with infrared experimental verification introduced herein needs to be combined with heat transfer theory and materialogy to serve for further structural design and optimization of thermoelectric modules and TEG, so as to improve the overall exhaust heat utilization and enhance the power generation.

Acknowledgments

This work was funded by the International Science and Technology Cooperation Program of China (Grant no. 2007CB607501) and General Motors Corporation and Wuhan University of Technology (No. 2011DFB60150).

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